SYSTEM ARCHITECTURE AND
INVESTMENT ANALYSIS

Redundant Radionavigation Service in the National Airspace System

An Analysis of Needs and an Assessment of Alternatives beyond 2010

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FAA Architecture and System Engineering Directorate

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1 Introduction

This report discusses the need for providing a redundant radionavigation capability to support satellite-based navigation (Satnav) and compares several techniques to sustain a navigation capability in the event of a Satnav disruption.

FAA's plans for the transition to Satnav[1,2,3] have until now indicated that the Global Positioning System (GPS) augmented by the Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS) would become the only means of radionavigation in the National Airspace System (NAS). Inherent in these plans is the assumption that GPS/WAAS/LAAS will together satisfy the performance requirements to be:

- the only radionavigation system installed in an aircraft to support operations anywhere in the NAS, and
- the only radionavigation service provided by the FAA to support NAS operations.

These assumptions are being challenged, primarily due to concerns about the relatively low-power signals received from the GPS satellites. As one example, the President's Commission on Critical Infrastructure Protection [1] highlighted GPS vulnerability and questioned its use as the only means of radionavigation in the NAS. The predominant concerns relate to a potential loss of service from intentional jamming, unintentional radio frequency interference (RFI), or ionospheric scintillation during severe solar storms. Intentional jamming is the most difficult threat to overcome. Current navigation aids (Navaids) may also be jammed, but GPS would appear to present an especially inviting target if virtually all flight operations became critically dependent on the uninterrupted reception of GPS signals.

Table 1-1 summarizes candidate solutions for each predominant GPS outage threat. Some of the solutions deal with all of the threats. These include independent ground navigation equipment, integrated GPS/inertial avionics, and radar vectors provided by air traffic controllers. The second civil GPS frequency solution is assumed to become available[4].

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1 Federal Radionavigation Plan, 1994, 1996

2 FAA's Plan for Transition to GPS-Based Navigation and Landing Guidance, July 1996

3 NAS Architecture Version 2.0, Version 3.0 (draft)

4 The Vice President announced that both a second and third civil frequency will be provided [2].

Table 1-1. GPS Outage Threats and Candidate Solutions

Outage Threat	*Candidate Solutions*
Intentional Jamming	• Integrated GPS/inertial • "Smart" aircraft antenna (phased array) • Independent ground navigation equipment • ATC radar vectors • Higher satellite power • Interference detection & response procedures • Avionics front-end processing
Unintentional RFI on L1	• Second civil frequency with ARNS[5] spectrum protection • Integrated GPS/inertial • Avionics front-end processing (filtering) • "Smart" antenna (phased array) • Independent ground navigation equipment • ATC radar vectors • Higher satellite power • Interference detection & response procedures
Ionospheric Scintillation	• Second civil frequency with ARNS spectrum protection • Integrated GPS/inertial • Avionics front-end processing (scintillation insensitive tracking loops) • Independent ground and airborne navigation equipment • ATC radar vectors • Higher satellite power

Appendix A includes more discussion of the outage threats listed in Table 1-1. Section 3 addresses several candidate solutions: ground-based Navaids, integrated GPS/inertial avionics, and controller vectors based on an independent surveillance system.

The analyses for GPS, WAAS and LAAS have shown that these systems are highly robust and that catastrophic failures are extremely improbable. There is concern, however, that all the failure modes that are known, together with those that may be unforeseen, could in the aggregate pose a safety risk or impose negative economic impacts to air transportation. Appendix B discusses several potential causes of outages.

[5] Aeronautical Radio Navigation Service – ARNS spectrum is protected from interference internationally for safety-of-life use.

Mitigation techniques are available that address most of these problems. These techniques involve:

- improvements to GPS (e.g., second civil frequency, increasing satellite transmission power),
- enhancements to user equipment (e.g., closely integrating GPS and inertial technology; digital signal processing to deal with narrowband emissions and scintillation),
- providing a ground-based Navaid infrastructure (e.g., a reduced network of VOR/DME's[6]), and
- operational procedures (e.g., air traffic controllers vectoring aircraft).

[6] Very High Frequency (VHF) Omni-Directional Range/Distance Measuring Equipment

2 Operational Needs for a Robust Radionavigation Capability

Four primary safety effects become apparent if GPS were the only means of radionavigation and subsequently became disrupted:

- Loss of approach and missed approach guidance
- Significant workload increases on pilots and controllers
- Loss of ability to hold based on own navigation
- Loss of terrain/obstruction avoidance assurance

The loss of approach and missed approach guidance during the landing phase of navigation is critical in those cases where procedural missed approach instructions (e.g., climb runway heading, turn left at 2,000 feet to heading 350) cannot be used in non-radar environments, or in cases where terrain, obstructions or other operations require course guidance. In the case where procedures can be followed but the destination of the missed approach is a waypoint, the procedure would need to be modified. The loss of navigation during landing and missed approach phases in instrument conditions would require air traffic control (ATC) support, which leads to workload increases.

A significant workload increase in itself would not lead directly to an accident. However, procedures and training would be required to deal with the loss of navigation and to assure that pilots and air traffic controllers are equipped to cope with sudden navigation outages affecting all aircraft in the airspace. The burden in the cockpit would depend upon the phase of operation. In the en route environment the pilot would need to revert to dead reckoning, i.e., continuing to fly the current heading, but would likely not be tracking timing for turns. The pilot would quickly become dependent on the controller for radar vectors. If in a non-radar environment, the pilot workload could become unacceptable. The challenge for the controller would be to quickly identify areas unaffected by the disruption and to provide radar vectors to guide the aircraft to these areas, to a suitable alternate airport, or to visual conditions. In the absence of a holding capability based on the aircraft's own navigation, there would be no tactical safety valve to regulate demand.

The absence of a holding capability would remove from the controller the ability to add order to chaos, i.e., to sequence aircraft for landing in a reduced capacity scenario, to deal with crossing traffic conflicts, and to provide a means to manage demand and retain safety. Holding in absence of any course guidance, while possible, is unacceptable in cases of medium to high traffic density.

Course guidance is critical for low-altitude en route navigation and for missed approaches and departures where terrain or obstruction clearances must be maintained. In non-radar environments, the pilot is responsible for maintaining clearance from terrain and obstacles. During an outage, the pilot could not continue on the planned flight path. If the aircraft were under radar control, the air traffic controller would need to provide terrain and obstruction clearance. Some airport missed approach procedures in mountainous terrain would need to be modified significantly to provide procedural missed approaches; this would not be possible in all cases. Figure 1-1 depicts the expected characteristics and probabilities of each outage threat. [7]

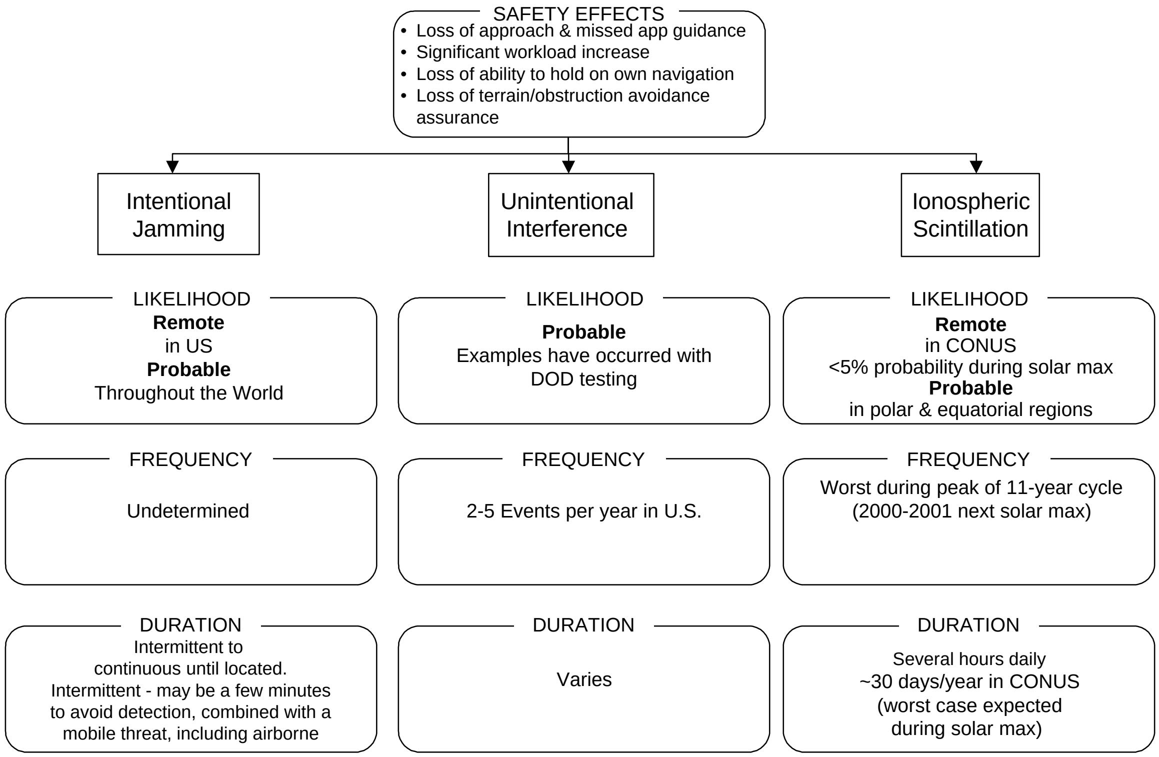

Figure 1-1. Characteristics of Satnav Outage Threats

In assessing operational needs, the four safety effects are the primary factors that must be considered. The FAA Air Traffic Service (ATS) believes that a loss of GPS service (in the absence of any other means of radionavigation) would have varying negative effects on air traffic operations. Both the service provider and the NAS users would be affected in varying degrees, ranging from nuisance events requiring standard restoration of capabilities to an inability to provide service within one or more sectors of airspace for a significant period of time. These issues are discussed in Appendix C in the context of "flight operational needs" and "flight planning needs." From an air traffic management perspective, immediate tactical measures are needed to balance demand and assure separation. As the extent of the disruption becomes known, traffic management strategies can be activated to manage the demand and sustain safe levels of operation. The need for local facility action and action on a national level to manage airspace use will require communications for routing information and supporting collaboration. Timely detection of navigation service problems is crucial to minimizing system disruption.

All of these planning needs will exist even with a backup capability. If any system backup is less than fully redundant in capabilities, then actions will be required to shift operations to this

[7] For the purposes of this analysis, "remote" is defined as having a probability of occurrence of 10^{-5} to 10^{-7} per flight hour. Similarly, "probable is defined as having a probability of occurrence of 10^{-3} to 10^{-5} per flight hour

backup capability. For example, if an ILS provides the backup for landing, a GPS disruption would generate a limited number of missed approaches, may require some holding or vectoring of traffic while pilots change to a different approach capability. This scenario would certainly generate increased voice communications at a time when the controller and pilot workloads are rising.

Section 3 of the report assesses several candidates for satisfying these operational needs: retention of a reduced set of ground-based Navaids; integration of inertial navigation techniques with GPS; and reliance upon ATC vectoring of aircraft.

3 Assessment of Candidates

This section assesses several candidate means of satisfying the operational need, discussed in Appendix C, during an outage of satellite navigation. The candidates are taken largely from Appendix D, which briefly describes a range of concepts for enhanced navigation redundancy in a future GPS/WAAS/LAAS environment.

It is assumed that any navigation capability in addition to Satnav equipage provides an "insurance policy" in the sense that aircraft owners or operators in most airspace would have the option to equip with this capability if their mission requires the additional robustness considering the potential of a GPS disruption. This assumption presumes an affirmative answer to the first of the two conditions posed earlier for a transition to Satnav, i.e., that GPS/WAAS/LAAS satisfy the performance requirements to be the only radionavigation system installed in an aircraft to support operations anywhere in the NAS. The assumption does *not* presume an answer to the second condition—that GPS/WAAS/LAAS satisfy the performance requirements to be the only radionavigation service provided by the FAA to support NAS operations.

It is likely that air carriers would equip with the "insurance" capability for economic reasons, including assurance of continued operations in the unlikely event of a widespread GPS outage. Equipping with the backup capability could also minimize possible fuel penalties that might otherwise be imposed to ensure safely flying to an alternate outside of a possible widespread outage. The candidates discussed address en route through nonprecision approach operations. In addition, it is assumed that at least one Instrument Landing System (ILS) would need to be retained at major airports to provide a backup precision approach capability, and where necessary to support international compatibility. ILS's may also be needed at a few remote airports where the distance to the closest major (ILS-equipped) airports is excessive.

3.1 Independent Ground Navaid Equipment

Retaining the existing ground-based infrastructure of VOR/DME Navaids solves the GPS jamming threat for equipped aircraft, but it would be very expensive for FAA to operate two completely redundant radionavigation systems. To reduce the replacement capital investment and operation and maintenance (O&M) cost, a possible candidate is a reduced, single-coverage network of high-altitude VOR/DME's. This "basic backup" network composed of a nominal 222 sites (160 in CONUS) allows aircraft equipped with inertial reference unit (IRU) and flight management computer (FMC) avionics to continue en route navigation using dual DME position updates to the FMC. It would also provide an NPA capability at selected airports, using either VOR/DME position updates to the FMC, or procedures based directly on VOR and DME guidance.[8] However, the network has not been fully analyzed to the level of detail necessary to fully address operational needs. Additional Navaids may be needed to assure the provision of course guidance for missed approaches and departures (where required), and where terrain or obstruction clearances must be maintained—particularly in non-radar environments.

[8] Aircraft lacking IRU/FMC capabilities would proceed to the VOR and conduct an approach and landing operation. This would not necessarily be to their originally planned destination.

Appendix E provides a coverage analysis of the candidate VOR/DME backup network. The coverage estimate portrayed in Figure 3-1 shows adequate en route coverage of two or more DME's for FMS/IRS updates at an altitude of 24,000 ft MSL[9]. Appendix F analyzes the potential for a DME saturation problem that could occur. The proposed backup network appears to have an aggregate DME capacity that can be described as marginal at best (relative to the projected air traffic), and may prove to be barely adequate during conditions of widespread instrument meteorological conditions (IMC). However, it is possible that operational procedures could be developed to adequately mitigate the impact of DME saturation during a disruption in Satnav service.

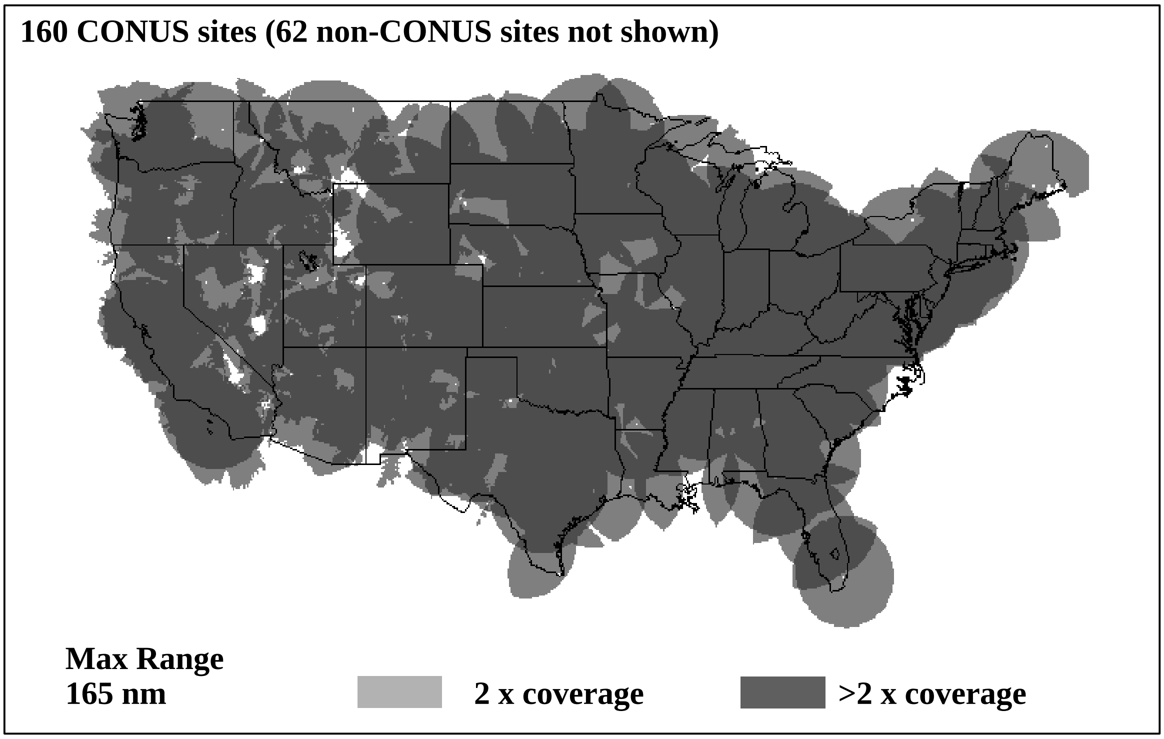

Figure 3-1. "Basic Backup Network" DME/DME Coverage At 24,000 Ft MSL

[9] The analysis did not compute whether the geometry was suitable for a DME/DME position solution; only the number of stations that were within range was determined. The accuracy of a DME/DME position solution depends upon the angle between the Navaids from the perspective of the aircraft. An "include angle" between 30 and 150 degrees is generally required for the position solution to be valid. A significant portion of the area covered by only two DME's may have geometry that is inadequate for a valid position solution. The coverage diagrams highlight the area covered by three or more DME's where the geometry more is likely to be adequate.

Figure 3-2 shows that coverage at lower altitudes may not provide complete en route coverage for lower-capability users. Appendix E shows that even if these aircraft were to climb to 12,000 feet, the coverage does not improve dramatically.[10] The coverage improves significantly above 14,500 feet, but many general aviation aircraft are unable to climb this high due to service ceiling constraints.

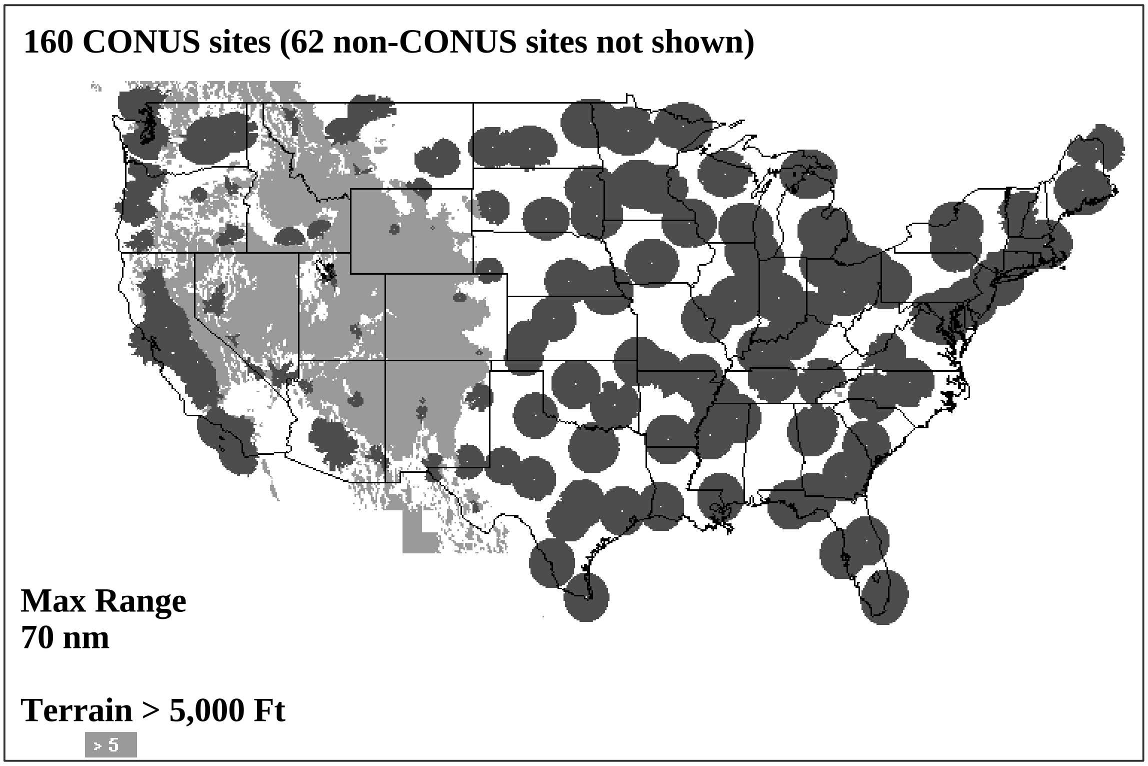

Figure 3-2. "Basic Backup Network" Single VOR/DME Coverage at 6,000 ft MSL

These stations would still provide an instrument approach and missed approach capability at an airport. Approach procedures based on VOR-only avionics and single-VOR ground equipment would need to be developed[11] to allow lower-capability users to conduct instrument approaches with this system. Further assessment would be needed to determine the adequacy of such a single-coverage network for the low-altitude users and to those without inertial systems. Assistance from ATC in the form of radar vectoring (discussed in Section 3.3) provides a possible means to deal with any operational shortcomings for low-altitude users. The acceptability of this solution may depend on the percentage of users equipped with an alternative navigation capability such as IFR-certified Loran[12] or an inertial system. An alternative to relying on the ground-based network for low-altitude operations is described in Section 3.2 based

[10] The coverage estimates are derived from a Boeing Navaid availability analysis. Boeing attributes VOR/DME's with an "operational service volume" that is significantly greater than the FAA "standard service volume," yet conservatively less than would be implied by simple line-of-sight calculations which are in any case invalid due to Navaid radiation patterns at low elevation angles. The operational service volume below 14,500 feet is 70nm compared to the FAA standard service volume of 40nm.

[11] One procedure currently in use requires the pilot to over-fly the Navaid, fly outbound, and execute a procedure turn at a specified time; then fly inbound for the final approach. This procedure is not widely implemented at the major airports included in the candidate backup network.

[12] Loran-C is expected to continue in operation through 2008. A decision to continue operation beyond that date has not been made, and would be dependent in part on industry's development of Loran avionics capable of being certified to conduct (nonprecision) instrument approaches.

on possible low-cost inertial technology currently being researched. Another alternative would be to retain Loran-C to allow low-altitude users an option to equip with IFR-certified Loran-C avionics. Appendix G discusses Loran-C system enhancements and avionics improvements that would need to be developed and implemented to achieve an instrument approach capability with Loran.

3.2 Integrated GPS/IRS

The navigation capabilities of IRU/FMC[13] equipment installed aboard many of today's commercial transport-category aircraft enable them to continue to conduct en route flights with far fewer radionavigation aids than is required by other types of aircraft without this equipment. This capability could enable IRU/FMC equipped aircraft to continue en route flight with minimal impact during a Satnav disruption using the Minimum Operational Network and perhaps even the Basic Backup Network of VOR/DME's (Section 3.1).

Appendix H briefly describes the equipage levels, characteristics and performance typical of today's IRU/FMC aircraft. Modern transport-category turbojet aircraft, when engaged in relatively stable en route flight, may be able to continue navigating safely an hour or more after losing radionavigation position updating. In some cases, this capability may prove adequate to depart an area with localized jamming or proceed under visual flight rules during good visibility and high ceilings. However, IRU performance without radionavigation updates degrades substantially faster on a maneuvering aircraft, and the viability of continued terminal-area navigation is unclear. There is no assurance of compliance with airspace requirements after executing a procedural turn or entering a holding pattern, even in en route airspace.

Several methods have been proposed to combine inertial measurements with GPS measurements to produce an integrated solution. These techniques are discussed in Appendix I. Perhaps most promising is research into "deeply integrated" techniques combined with innovative low-cost inertial technology. This research may lead to avionics for the general aviation (GA) market having more than 40 dB anti-jam capability and potentially selling for a few thousand dollars. The operational capability of this technology would be to greatly reduce the area affected by a given level of GPS jamming power[14], and then to provide inertial positioning within the affected area, allowing en route navigation through the affected area and perhaps even an instrument approach capability. Appendix I discusses the technical and operational capabilities of this technology in more detail. The expected availability of this capability for GA applications is in the 2005 to 2010 timeframe.

3.3 ATC Vectors

Aircraft equipped with either IRU/FMC using DME updates (assuming a network of VOR/DME Navaids) or integrated GPS/inertial (or Loran-C, with the constraints discussed in Appendix G), would be able to continue en route through nonprecision approach operations in the affected area of a GPS disruption. Unequipped aircraft would need to be vectored to an airport outside the affected area or to an airport in Visual Meteorological Conditions (VMC). Aircraft equipped

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[13] Inertial Reference Unit/Flight Management Computer

[14] Conversely, significantly greater jamming power would be required to affect the same area.

with a VOR (assuming a network of VOR/DME Navaids) may need to be vectored into an area with VOR coverage, to an airport that has an instrument approach defined using VOR, to an airport outside the affected jamming area, or to an airport in VMC.

If a majority of users equip with either IRU/FMC or integrated GPS/inertial, or with an approach-capable Loran, then ATC should be able to handle the balance with vectors based on an independent surveillance system. Additional research may be necessary to validate this concept in terms of the impact to air traffic controller workload and the sensitivity to the proportion of backup-equipped aircraft.

4 Current Transition Strategy

The current strategy for the transition to Satnav is articulated in the 1996 Federal Radionavigation Plan (FRP). More specific detail appears in the FAA's Plan for Transition to GPS-Based Navigation and Landing Guidance (July 1996). The transition begins in mid-1999 with the initial implementation of the Wide Area Augmentation System (WAAS)[15].

The most significant step in the transition is the achievement of WAAS full operational capability[16]. WAAS FOC will provide a robust "enabling technology" that will allow the eventual phase-down of conventional ground-based Navaids. At FOC, WAAS will comply with its end-state requirements, providing a level of availability sufficient to consider replacing the existing VOR/DME and NDB facilities and many Category I ILS facilities. The phase-down is nominally planned to begin in 2005—or four years after WAAS FOC—based on the anticipated user equipage with Satnav avionics and the resulting decreased use of the conventional Navaids.

The end of the transition is currently planned to occur in 2010 with the phase-out of all remaining ground-based Navaids. (However, these plans were based on the assumption that Satnav would become the only radionavigation service provided in the NAS.) The nine-year transition period that begins with WAAS FOC is primarily intended to allow the user community a reasonable period of time to equip with Satnav avionics.

4.1 Current Ground Network

The NAS is currently served by several radionavigation systems that support en route and terminal area navigation, as well as nonprecision approach operations. These include VOR with associated DME, TACAN, Loran-C, nondirectional beacons (NDB), and GPS. The inventory of FAA-operated systems includes (1) 1,074 VOR's, VOR/DME's and VORTAC's, and (2) 744 NDB's.

VOR is the principal aircraft navigation system in the U.S. and, to a large extent, in the rest of the world[17]. It forms the basis of the current low and high altitude route structures and provides an NPA capability at most airports in the NAS. In addition to forming the en route network, many VOR's have been added in recent years to assist in organizing arrivals and departures at major terminal areas. This has been necessary because, without special avionics that allow RNAV[18] capability, aircraft using VOR's must fly on radials directly to or from a VOR station. This is one of the principal limitations of VOR navigation.

TACAN is functionally similar to VOR/DME but is primarily used by DOD aircraft. Both use the same ranging component (DME), but the TACAN azimuth component operates in a different

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[15] WAAS Initial Operational Capability (IOC) is currently planned for July 1999.

[16] WAAS FOC is currently planned for December 2001. Any change in WAAS FOC will require a reconsideration of the proposed schedule for phasing-down current Navaids.

[17] European airspace is in the process of being restructured around RNAV capabilities (in large part based on GNSS capabilities).

[18] RNAV, or Area Navigation, involves establishing and maintaining a flight path on any arbitrarily chosen course that remains within the coverage area of the navigation sources being used. In a practical sense it means navigating between waypoints defined by their geographic coordinates (latitude, longitude) rather than flying directly to (or from) point-referenced Navaids such as VOR/DME's or NDB's.

radio-frequency band than VOR. The FAA-operated VORTAC's combine VOR, DME, and TACAN into a single facility.

NDB's serve two principal functions in the NAS: as stand-alone NPA aids at smaller airports; and as compass locators, generally collocated with the outer marker of an ILS to assist pilots in getting on the ILS course in a non-radar environment. In addition to these functions, approximately 90 NDB's are used in Alaska to define low-frequency airways. Because of the heavy reliance on NDB's in Alaska, there must be special consideration in their phase out.

Loran-C is a low-frequency, long-range navigation system operated by the U.S. Coast Guard. Twenty-eight Loran transmitters provide signal coverage throughout the continental U.S. and most of Alaska. Loran has provided reliable, all-weather navigation for marine users since World War II. Today, Loran-C is used widely in general aviation for visual flight rule (VFR) en route and terminal area navigation. It is used to a lesser extent for supplemental instrument flight rule (IFR) en route and terminal area navigation.

Two systems are used in the NAS for precision approach and landing—ILS and MLS[19]. ILS is the current worldwide standard for precision approach and landing. ILS provides lateral guidance by a fixed "localizer" beam and vertical guidance by a fixed "glideslope" beam. MLS was developed in the 1970's as a replacement for ILS. However, as Satnav technology showed increasing promise for precision approach applications, and lacking widespread industry support for MLS, the FAA terminated the MLS acquisition program. The current FAA inventory includes 1,062 Category I, II, and III ILS's and 29 Cat I MLS's.

4.2 Phase-Down Of Ground-Based Navaids

The infrastructure of ground-based Navaids enjoys great user confidence based upon decades of operational experience. Transition to a totally new system represents a substantial undertaking—one which will require a major investment of resources by both the FAA and the aircraft owners and operators. Three essential prerequisites must be met for such a massive transition to take place:

> *System Performance* – Through analyses, flight tests, and operational experience, aircraft operators and the FAA must be convinced that the new system meets their requirements for accuracy, integrity and reliability. This must be proven with substantial operational experience.
>
> *Operational Benefit* – The aircraft operator must perceive sufficient operational benefit to warrant an investment in the new technology.
>
> *Transition Period* – The aircraft operators must have sufficient time to recoup their investment in conventional avionics. Although many avionics systems have been used for 15 to 20 years or more, a reasonable compromise must be reached between the FAA's desire for a rapid transition (to avoid further investment in ground-based Navaids) and the aircraft operators' desire to use current avionics as long as possible.

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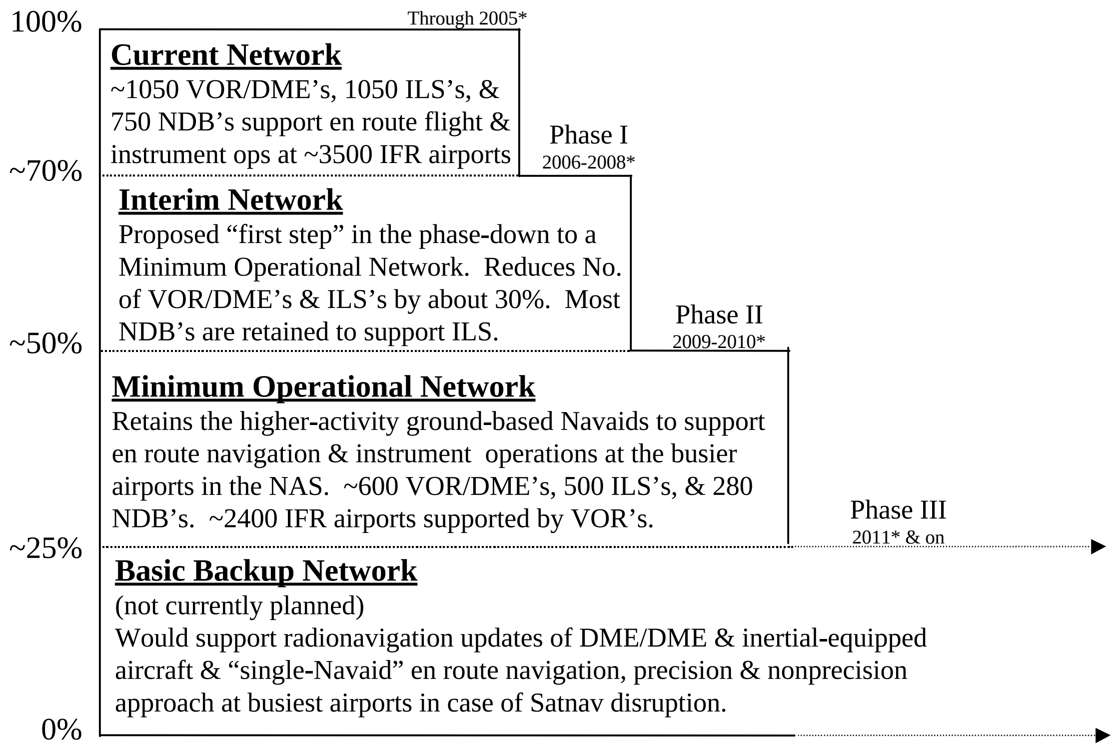
[19] Microwave Landing System

The transition period begins when the capability is established for a pilot to perform navigation procedures throughout the NAS using Satnav as the only means of radionavigation aboard an aircraft. This will occur when WAAS achieves its full operational capability and procedures to use the new capability have been published (i.e., precision and nonprecision Satnav instrument approach procedures). Prior to this, even new aircraft must be equipped with avionics for the conventional ground-based Navaids. The transition period ends when the conventional Navaids have been reduced to the extent that they are unnecessary for NAS operations.

The reduction in Federally provided Navaid services can be performed in several distinct steps. This approach would allow the FAA to begin the phaseout gradually, providing users sufficient time to equip with Satnav avionics. A more abrupt transition would be too disruptive to NAS operations and would place too great a burden on the users. The proposed phase-down strategy is depicted in Figure 4-1.



*Note: Dates are currently planned, but will be updated as Satnav program milestones are achieved; as the actual performance of Satnav systems is documented; and as users equip with Satnav avionics.

Figure 4-1. Proposed Navaid Phase-Down Steps

The proposed transition strategy involves a two-step phase-down from the current full coverage network of Navaids to a reduced network that supports a substantial number of currently certified airways, jet routes, and instrument approach procedures. This network, termed the Minimum Operational Network, is a scaled-down version of the current infrastructure of VOR's, ILS's[20], MLS's, and NDB's.[21] The proposed phase-down strategy would provide the FAA and the

[20] ILS includes all equipment required for selected approach procedures (Marker Beacons, Compass Locators, etc).

[21] VOR test facilities (VOT), Localizer-only facilities (LOC), and Simplified Directional Facilities (SDF) may be turned off at the beginning of the decommissioning schedule.

airspace users with a safe recovery and sustained operations capability in the event of a disruption in Satnav service. The Navaid phase-down can be initiated after the following conditions have been met:

- WAAS has achieved its full operational capability (FOC) and has been approved as an only means of radionavigation for a given flight operation (At FOC, WAAS will comply with its end-state requirements, providing a level of availability sufficient to replace existing VOR/DME and NDB facilities, and many Category I ILS facilities);
- Procedures to use the new WAAS capability have been published; and
- A majority of the airspace users have equipped with appropriate GPS/WAAS avionics.

The phase-down is planned to begin in 2005 based on projected Satnav program milestones and anticipated user equipage rates.

The specific Navaids that would no longer qualify for Federal support, at each step of the phase-down, would be determined based on specific criteria, currently under development. Navaids supporting en-route procedures would be decommissioned. Navaids supporting terminal procedures could be decommissioned or transitioned to a non-Federal sponsor.

The discontinuance criteria would be published as early as possible and well ahead of the phase-down. A site-specific list of Navaids fitting the discontinuance criteria would be published later—perhaps at the time of WAAS FOC. The advanced site-specific notice would afford users the opportunity to plan their transition to Satnav based upon the operational schedule for the specific Navaids they use most often.

- *Phase I* –Many currently under-utilized VOR's and ILS's would be discontinued at the first step of the phase-down. Preliminary analysis indicates that approximately 350 VOR's and 300 ILS's might be turned off at this first step. (The population of NDBs would remain essentially intact to support ILS approaches.) Although this represents an approximate 30% reduction in the number of Navaids, it would be expected to cause a relatively minor impact on the NAS, as depicted in Table 4-1.
- *Phase II* – The second step, planned to occur in 2008, further reduces the population of ground-based Navaids to the level of the Minimum Operational Network. The Phase II Navaids are intended to support continued operation in the NAS by those aircraft not yet equipped with Satnav avionics, albeit at a reduced level of efficiency. Although this represents an approximate 50% reduction in the number of Navaids, the remaining network would continue to support a robust set of IFR operations (Table 4-1).
- *Phase III* – As mentioned earlier, present plans are to complete the transition to Satnav with the phase-out of all the remaining ground-based Navaids. However, those plans were based on the assumption that Satnav would become the only radionavigation service provided in the NAS. A more conservative approach to consider may be to instead step-down to a subset of ground-based Navaids that would continue to support Satnav operations beyond 2010. A candidate "Basic Backup Network", consisting of a nominal 160 VOR/DME's in CONUS plus 62 sites in Alaska, Hawaii and the Territories, is presented in Appendix E. The network is also

portrayed in Table 4-1. Because the network would be essentially incapable of supporting scheduled operations, no statistics are presented on the number of approaches, enplanements or instrument operations that it would support.

Table 4-1. Capabilities And Impacts During Phase-Down[22]

Phase	*Description*	*VOR's*	*ILS's*	*Airports Served*	*Approaches*	*Enplane-ments)[23]*	*IOPS[24]*	*Total Ops*
	All Airports			5,902	2.5 M/yr	760 M/yr	46 M/yr	91 M/yr
-	Non-IFR Airports			2,323	2.32 %	3.96 %	3.25 %	10.98 %
0	Current Network	1,074	1,062	3,579	97.68 %	96.04 %	96.75 %	89.02 %
I	Interim Network	719	775	2,710	97.68 %	95.89 %	96.75 %	82.19 %
II	Minimum Operational Network	614	518	2,414	94.85 %	95.42 %	95.04 %	76.38 %
III[25]	Basic Backup Network	222	332	-	-	-	-	-

4.3 Transition Cost Analysis

This section presents a summary of the estimated costs to sustain and operate the ground-based Navaids based upon several operational scenarios. Costs are projected over a 20-year life-cycle, beginning in 2001 and ending in 2020.

a. Operate the current network of Navaids indefinitely. This is the “base case”.
b. Phase-down only to the Minimum Operational Network.
c. Phase-down to the proposed Basic Backup Network.
d. Phase-out all ground-based Navaids. This is the current plan.

The costs are summarized in Table 4-2. Appendix J summarizes the assumptions used in the analysis, together with detailed cost spreadsheets for each scenario.

Table 4-2. Transition Cost Summary ($M[26])

	O&M	F&E	Decommissioning	Total
a. Base Case	$2,619.7	$1,832.2	$0.0	$4,451.9
b. Min Op'l Net	$1,832.2	$778.3	$217.8	$2,828.4
c. Basic Backup	$1,517.8	$361.3	$348.9	$2,228.0
d. Total Phaseout	$1,094.2	$227.4	$471.6	$1,793.2

22 Based on 1995 and 1996 Terminal Area Forecast (TAF) data

23 Air carrier enplanements – includes originating, stopover, and transfer passengers of scheduled and nonscheduled commercial air carriers.

24 Instrument Operations

25 Proposed; not currently planned.

26 All costs are expressed in constant 1998 dollars.

It has been suggested that the O&M costs in a “backup” scenario, where the Navaids would be relegated to the sole role of supporting Satnav operations, might be significantly reduced from the current estimates. This may be possible if the maintenance and restoration requirements were changed from “instantaneous” or “on demand” to a less-immediate philosophy—perhaps “within 48 to 72 hours”.

5 Summary

FAA's plans for transitioning to Satnav as the only radionavigation service provided in the NAS are being challenged. The predominant concerns relate to a potential loss of service from intentional jamming, unintentional radio frequency interference (RFI), or ionospheric scintillation during severe solar storms.

- The effects of jamming and unintentional interference are primarily to increase the workload of both the users and the service providers. Pilots and controllers will work together to assure safety, but the loss of navigation and landing capabilities increases the demand for services. Operational restrictions would likely be necessary to balance demand and assure safety.
- Solar effects are expected to have only minimal impact on CONUS airspace. The greatest impact is expected in the polar regions and near the equator. Most aircraft operating on polar routes are equipped with inertial systems and can operate for many hours between radionavigation updates before violating separation requirements. Some care will be needed in high-latitude and equatorial zone Satnav-based instrument approaches at night.
- A loss of GPS service in the absence of any other means of radionavigation would have varying negative effects on air traffic operations. These effects range from nuisance events requiring standard restoration of capabilities to an inability to provide service within one or more sectors of airspace for a significant period of time. The FAA Air Traffic Service has articulated requirements for a continued navigation capability in the event of a disruption of Satnav service.

Several solutions have been identified to help mitigate the effects of a Satnav service disruption, but each has its limitations.

- Most problems related to solar disturbances can be alleviated with proper receiver design. The second civil frequency planned for GPS will further help alleviate the impacts of both solar activity and unintentional interference, but it may be 2013 or later before a full constellation of dual-frequency satellites is available. The cost implications of a second civil frequency are not yet defined.
- Modern transport-category turbojet aircraft, when engaged in relatively stable en route flight, may be able to continue navigating safely an hour or more after losing radionavigation position updating. In some cases, this capability may prove adequate to depart an area with localized jamming or proceed under visual flight rules during good visibility and high ceilings. However, IRU performance without radionavigation updates degrades substantially faster on a maneuvering aircraft, and the viability of continued terminal-area navigation is unclear. There is no assurance of compliance with airspace requirements after executing a procedural turn or entering a holding pattern, even in en route airspace.
- Integrated GPS/inertial avionics having significant anti-jam capability could greatly reduce the area affected by a GPS jammer or by unintentional interference. Research is proceeding to develop this technology, with an expectation that it might be marketed to the general aviation community—in the 2005 to 2010 timeframe.

However, significant certification challenges will be encountered, and some users may still find this technology to be unaffordable.

- A basic backup network composed of a nominal 222 conventional VOR/DME Navaids would allow aircraft equipped with IRU/FMC avionics to continue en route navigation using dual-DME position updates. It would also provide a nonprecision approach capability at selected airports, using either VOR/DME position updates to the IRU/FMC, or using procedures based directly on VOR and DME guidance. However, the candidate network may have a marginal DME capacity and may not provide complete en route coverage for low-altitude users—who may need to be vectored into an area with VOR coverage or to an area in VMC. Additional Navaids may also be needed to assure the provision of course guidance for missed approaches and departures (where required), and where terrain or obstruction clearances must be maintained—particularly in non-radar environments.
- Low-altitude users may have an option to equip with IFR-certified Loran-C avionics, pending the improvements needed to achieve an instrument approach capability with Loran. The widespread installation of approach-capable Loran avionics could preclude the need to retain VOR's for these users. The cost to sustain a network of DME's alone (for updating IRU/FMC aircraft) could be substantially less than sustaining the same number of VOR/DME's.
- If the aircraft in a majority of operations are equipped with FMC or integrated GPS/inertial avionics (assuming a network of VOR/DME Navaids), or with an approach-capable Loran, then ATC should be able to handle the balance with vectors based on an independent surveillance system. Additional research may be necessary to validate this concept in terms of the impact to air traffic controller workload and the sensitivity to the proportion of backup-equipped aircraft.
- The candidates discussed address en route through nonprecision approach operations. At least one ILS (or MLS) would need to be retained at major airports to provide a backup precision approach capability, and where necessary to support international compatibility. ILS's may also be needed at a few remote airports where the distance to the closest major (ILS-equipped) airports is excessive. The candidate Basic Backup Network includes a nominal 233 Category I and 99 Category II or III ILS's.

6 Recommendations

The varied threats described in this report and their resultant potential effects on safety and economics will likely remain a concern to users even after WAAS achieves a final operational capability and users gain experience in its use. For these reasons, retaining a reduced infrastructure of ground-based radionavigation aids well beyond 2010 appears to be justified—at least until reception of the second civil GPS frequency becomes commonplace in WAAS receivers.

The cost of sustaining this capability with a reduced network of today's ground-based Navaids is substantial. The cost must be weighed against the potential safety and financial impacts of a GPS outage—particularly in a busy terminal area during instrument meteorological conditions. If the threats from unintentional RFI and solar effects are mitigated sufficiently by a second civil GPS frequency, then the remaining vulnerability is from intentional jamming. Retention of a redundant capability would mitigate the jamming threat, but the cost of this "insurance policy" is high.

The Basic Backup Network of VOR/DME's and ILS's discussed in the report may have a marginal DME capacity for transport-category aircraft and does not provide complete en route coverage for low-altitude users. This capability will likely prove suitable only in the cases of a localized problem. The Minimum Operational Network shows dramatically better low-altitude coverage, but requires significantly more facilities—at a substantially higher cost ($2.8B vs. $2.2B over a 20-year life-cycle, 2001 through 2020).

It would seem reasonable for the FAA to plan to rely on each of the options identified in Section 3 and to periodically adjust their plans. Specifically, it is recommended that the FAA:

- Plan to maintain a reduced network of VOR/DME and ILS Navaids indefinitely beyond 2010 to support Satnav operations. A basic navigation capability is required, in the event of a Satnav disruption, to meet the operational needs presented in Appendix C. The reduced network should support updates of DME/DME and IRU/FMC-equipped aircraft and should provide a reasonable level of service to lower-capability aircraft. The network need not be so robust that it supports normal operations for users not equipped with Satnav avionics. A reasonable network lies somewhere between the Basic Backup Network and the Minimum Operational Network.
- Closely coordinate with airspace users and ATC providers the plans to phase-down the existing network of ground-based Navaids. The phase-down plans need to remain flexible, and may need to be adjusted as Satnav program milestones are achieved, as the actual performance of Satnav systems is demonstrated, and as users equip with Satnav avionics.
- Assess the duration that IRU performance is truly acceptable for en route operations by transport-category aircraft after losing radionavigation position updating.

- Analyze the impact of Satnav disruptions on air traffic controller workload and the sensitivity to the proportion of backup-equipped aircraft.
- Encourage the expedited development of integrated inertial/GPS technology and support industry in certifying this technology for general aviation and other lower-capability users.
- Monitor the potential development of approach-capable Loran-C avionics and support industry certification efforts.
- Encourage the development of dual-frequency Satnav avionics
- Adjust Navaid phase-down plans as technology matures.
- Continue to examine the threats to satellite navigation and identify appropriate mitigation techniques.

REFERENCES

1. *Critical Foundations – Protecting America's Infrastructure*. The President's Commission on Critical Infrastructure Protection, October 1997
2. *GPS to Provide Two New Civilian Signals.* Press release DOT 55-98, U.S. Department of Transportation, Office of the Assistant Secretary for Public Affairs. March 30, 1998.